DOES VELOCITY REDISTRIBUTION REALLY ENHANCE THE HE 304 Å LINE TO OBSERVED INTENSITIES?

Stuart Jordan[1], Vincenzo Andretta[1], Adriana Garcia [2], Jeffrey Brosius, [3], William Behring [1]

[1]Goddard Space Flight Center
[2]Observatório Astronómico da Universidade de Coimbra
[3]Raytheon ITSS

ABSTRACT

Previous work by this group has demonstrated that small-scale nonthermal velocities probably play a significant role in enhancing the intensity of the He II 304 Å line above values predicted by the static atmopsphere NLTE theories, and more in conformity with Skylab and SOHO observations. This presentation briefly summarizes the evidence for this conclusion, emphasizing SOHO and correlated ground-based observations, of which examples are presented. However, in contrast to the previous studies, the tact taken here is more critical, asking the question "Can velocity redistribution fully explain the observations of the 304 Å line, and what counter-indications and problems remain?" The conclusion reached is that, while velocity redistribution plays a significant role in the intensity enhancement, it may not be the whole story. Some other mechanism, associated with velocity filtration, may be at work.

Key words: transition region, He resonance line formation.

1. BACKGROUND OF THE PROBLEM

It has been known since Skylab days that the observed emission in the He II 304 Å line greatly exceeds the value calculated with static atmosphere NLTE models (Jordan, 1975). This result has been confirmed with SOHO observations (Macpherson & Jordan, 1999). Efforts to explain this phenomenon by incorporating diffusion into these models, suggested by Shine et al. (1975), were not successful (Fontenla et al., 1993). Jordan (1980) noted that any process that could increase the temperature of the electrons producing the 304 Å emission would greatly enhance it, as long as the line was dominated by collisional excitation. However the line-formation mechanism had not been established at that time, and Zirin (1975) had provided arguments suggesting the line might be dominated by photoionization-recombination (p-r), stimulated by coronal radiation.

Part of the problem was the absence of 304 Å observations with sufficiently high resolution, simultaneously, in the spatial and spectral parameters. This situation was improved significantly during the 1989 flight of the Goddard Solar Extreme-Ultraviolet Rocket Telescope and Spectrograph (SERTS). Observations from this flight led to the determination that the collisional excitation mechanism was dominant in at least the quiet regions of the solar atmosphere (Jordan et al., 1993). This led us to explore one of the two possiblities noted by Jordan (1980) for exposing the helium ions to high-temperature electrons. (We comment on the alternative at the end of this paper.) This possibility, which we call '*velocity redistribution*,' is that comparatively large-magnitude, small-scale velocities carry a significant fraction of the ions to a region of higher temperature thermal electrons, where the collisional excitation takes place. Since the 304 Å line is formed in the lower transition region (TR), where the temperature gradient is large, the effect of this velocity redistribution will be to greatly enhance the emission over the value obtained with electrons at the ionization equilibrium temperature.

The following summary of what we did is developed in detail in Andretta et al. (1999). Here we summarize our test of the velocity redistribution hypothesis, using observations from SERTS-91 and SERTS-93. We then describe further tests of this hypothesis, using correlated SOHO and ground-based observations. The final section offers a brief discussion of the results, with comments on current plans and future needs.

2. TESTING FOR VELOCITY REDISTRIBUTION WITH SERTS

A description of the EUV solar spectrum from SERTS-91 and SERTS-93 is found in Brosius et al. (1996). We used the 304 Å spectra from this study. The spatial and spectral resolutions are estimated to be 5 arc-sec and 55 mÅ respectively. We also use the same criteria for quiet Sun and active region as in Brosius et al.

We were immediately struck by the anti-correlation between line intensity and line width. This can be seen for the two cases in Figure 1, which is dis-

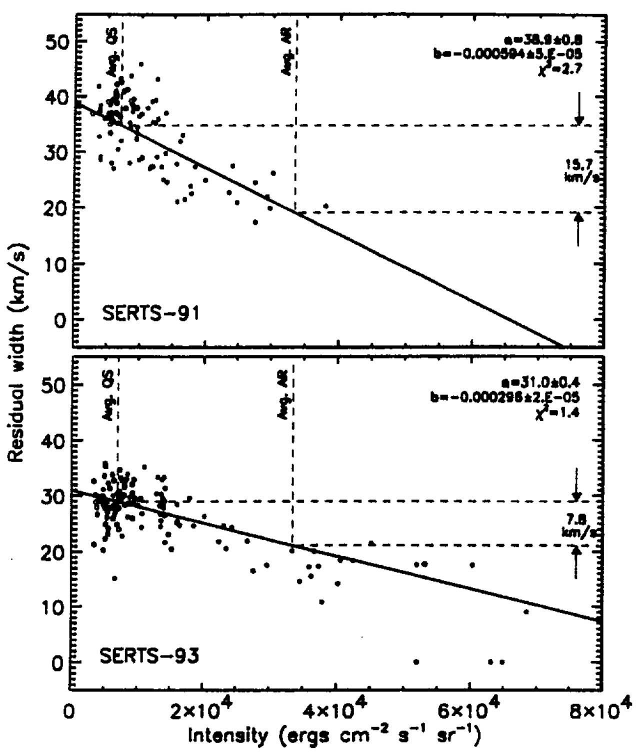

Figure 1. Nonthermal line widths *vs.* intensities from SERTS flights.

cussed in more detail below. There is strong evidence that the 304 Å line is everywhere optically thick (Hearn, 1969). The observed anticorrelation is not what one would normally expect from a static atmosphere. The excess line width in the lines from the quieter regions was a clear indication that significant microturbulent velocities existed on a spatial scale smaller than the 5 arc-sec resolution of the instrument, especially in view of the highly gaussian nature of the profiles and the relatively small relative Doppler shifts. This suggested that these relatively small-scale movements of the He II ions might be sufficient to greatly enhance the 304 Å intensity above the static atmosphere value.

To test this, we developed a simple first-order theory to assess the effect of different values of the small-scale nonthermal velocity V_{NT}, the TR gradient ∇T_e, and the ionization equilibrium temperature T_{ei}. For details, see Andretta et al. (submitted). The salient results are best represented by two parameters that we call '*the velocity redistribution parameter* M,' and '*the intensity enhancement parameter* Y.' The velocity redistribution parameter M is given by

$$M = (V_{NT} \times \nabla T_e)/P_e \ , \qquad (1)$$

while the intensity enhancement parameter Y is defined as

$$Y(\text{He II 304 Å}) = I_f(T_{ef})/I_i(T_{ei}) \ , \qquad (2)$$

which can be reduced to

$$Y(\text{He II 304 Å}) = f(T_{ei}, M) \ . \qquad (3)$$

In light of these results, it becomes important to determine the magnitude of the small-scale nonthermal velocities of the He II ions. To do this properly requires a detailed NLTE analysis of the spectra that we are just beginning. However, we can easily estimate a conservative lower limit on V_{NT} from the data plotted in Figure 1. The excess line-width in the quiet-Sun spectra, compared to the more intense active-region spectra, cannot be due to radiative transfer effects, and therefore affords us a measure of the *minimum mean value for the actual nonthermal velocity of the He II ions.* From the difference between the average residual line widths (after removing thermal and measured instrumental widths) from the quiet-Sun and the active-region spectra, we can estimate this mean lower limit on the ion velocity. This too is illustrated in Figure 1. While the values in the range 8-16 km s^{-1} are insufficient to provide an intensity enhancement as great as a factor of 10, it should be recalled that these values are extremely conservative. Figure 2 shows how the combined effects of increased temperature gradient and higher nonthermal He II ion velocities will increase both the temperature at which emission occurs (left-hand side of Figure 2) and the subsequent enhancement (right-hand side). Combinations of realistic TR temperature gradients with nonthermal velocities of the He II ions close to the limit determined can easily provide enhancements on the order of 5, and it is quite possible that the more realistic, higher value for the actual nonthermal velocity of the ions might yield an enhancement twice that great.

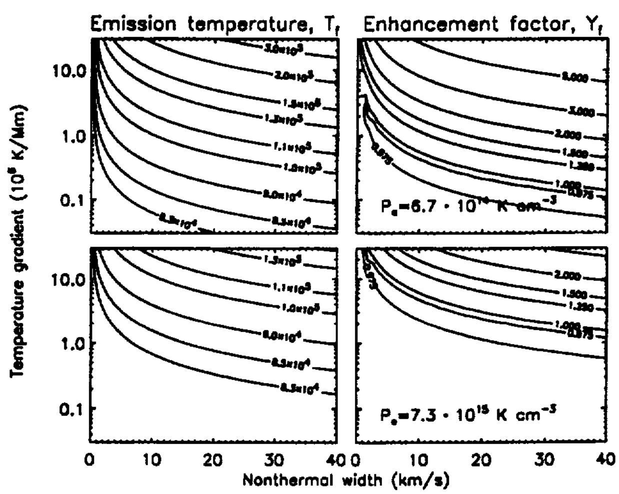

Figure 2. Effect of ∇T_e and V_{NT} on emission temperature and enhancement.

3. FURTHER TESTING USING CORRELATED SOHO AND GROUND-BASED OBSERVATIONS

If velocity redistribution is influencing the emission level of collision-dominated lines, the effect will be strongest for the shortest wavelength lines, as pointed out by Jordan (1980). This is because the most parameter-sensitive term in the source function for these lines is the exponential term $\exp(h\nu/kT_e)$. From simultaneous spectroheliograms taken with the SOHO CDS Normal Incidence Spectrograph (NIS) in

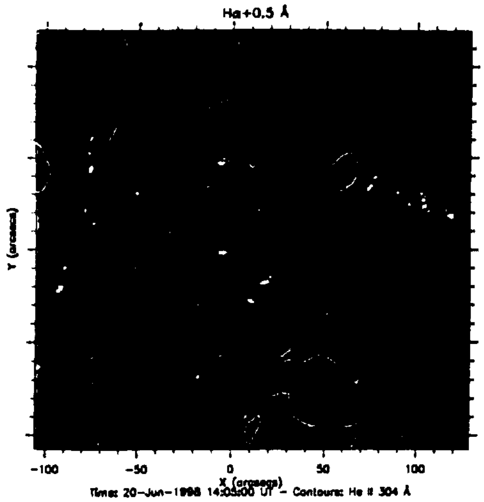

Figure 3. Projection of 304 Å intensity onto Hα red wing.

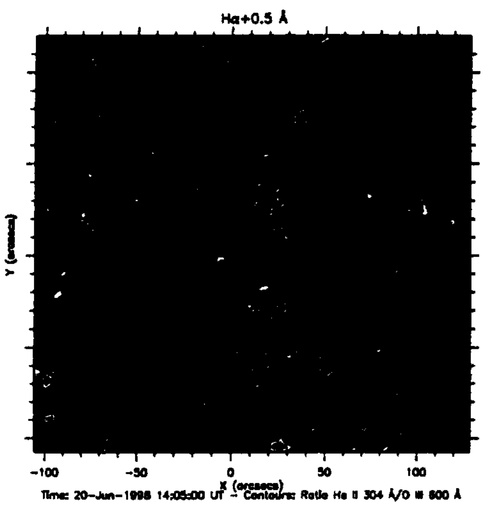

Figure 4. Ratio of 304 Å to O III 600 Å intensities projected onto Hα red wing image of Figure 3.

second-order 304 Å and in O III 600Å we can examine the change in the ratio of these lines as we proceed from the boundary of a chromospheric cell to the center. As we proceed from the more active conditions on the boundary of the cell into the center we would expect this ratio, which we call R, to increase.

We conducted this test, using essentially simultaneous coregistered ground-based spectroheliograms in the +0.5 Å red wing of Hα (bandpass of $\Delta\lambda = 0.2\AA$) to establish the underlying chromospheric network. As expected, when the 304 Å and 600 Å lines are coregistered with these Hα spectroheliograms, there is a significant anticorrelation between the emission in both of these TR lines and the brightness in Hα, corresponding to greater intensity in both TR lines at the boundaries. (The cell boundaries are well described by the Hα 'coarse dark mottles' first described by Beckers (1968).) However, when the ratio R described above is correlated with brightness in Hα, the correlation is positive, corresponding to a relative increase in the 304 Å line as 'quieter' conditions prevail. This can be seen visually in Figures 3 and 4, respectively.

The procedure we followed for establishing these results is statistical. We first coregister 4 x 4 arcmin FOV CDS spectroheliograms in the two TR lines with the red-wing Hα spectroheliograms and then divide the region imaged into four quadrants and determine the correlation coefficient for each quadrant. The values for the correlation coefficient varied somewhat over the entire FOV, but the same significant trend was revealed in all quadrants. For the projection of the second-order 304 Å onto Hα, we obtained over the entire FOV a value of -0.516. For the the O III 600 Å line projected onto Hα, the value was almost the same, namely -0.522. On the other hand, when the ratio R of 304 Å to 600 Å is projected onto $H\alpha$, the full FOV correlation coefficient is 0.311, not as strong as one might wish, but exhibiting the expected trend. We note that this correlation coefficient would undoubtedly be stronger if the second line chosen had been one of the longer wavelength TR lines of C IV or Si IV, but instrumental limitations precluded this. The reason for this is, again, the predominance of the tempeature-sensitive exponential source term for a collision-dominated line.

4. DISCUSSION

The evidence of our tests is that velocity redistribution contributes substantially to enhancing the He 304 Å intensity in the quiet Sun. (We emphasize that some of these arguments do not apply to the active region, and make no claims for the situation there.) On the basis of these tests, we feel it is not unreasonable to achieve at least a factor of 5 enhancement, and one twice as large cannot be ruled out.

Is this enough? Perhaps not. Macpherson and Jordan (1999) conclude from their analysis of SOHO spectra that the required intensity enhancement could easily exceed a factor of 10, and that a value twice as large might be encountered. We cannot make a definitive statement in the absence of a more detailed analysis of our observations, but our educated guess at this time is that enhancements exceeding a factor of 10 are unlikely from velocity redistribution, unless the local temperature gradients are huge (transitions to coronal temperatures in distances on the order of 10 km).

If velocity redistribution alone cannot achieve the required intensity enhancement, what other process might be at work? Scudder (1992) has proposed that a non-Maxwellian distribution of high-energy electrons generated in the sub-coronal solar atmosphere could produce the rise to coronal temperatures by a process called '*velocity filtration*.' In this process, the local distribution becomes increasingly biased toward the higher electron energies as one proceeds upward through the atmosphere. Thus, according to this picture, the 'hottest' electrons travel the farthest and yield a coronal temperature. A number of unsolved problems remain, including identification of a mechanism for maintaining the nonthermal electron distribution in the still relatively high density region where the 304 Å line is formed. Addressing this problem, Viñas (2000) has proposed a high frequency plasma oscillation capable of generating and maintaining the nonthermal electron distribution there. However, it remains to be shown that conditions for producing this plasma oscillation are met in the lower solar atmosphere. Clearly the velocity filtration hypothesis is worth pursuing, but requires further investigation.

Further research on velocity redistribution must include: 1) a proper NLTE fitting of the 304 Å spectra already available and to be obtained, primarily to better assess the line broadening mechanism and to refine (probably to increase) the estimate of the nonthermal velocity of the radiating He II ions, 2) obtaining better models of the low TR from SOHO/SUMER observations that were obtained simultaneously with the CDS observations reported above, and 3) checking for consistency with all other TR and helium results. The first steps in all these areas are now underway. The new SERTS normal-incidence telescope should provide 304 Å spectra at double the former spatial resolution, greatly facilitating the first of these studies.

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